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M. F. NETWORK PLANNING:
the coverage under daytime conditions from a network of transmitters arranged in a uniform lattice

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MF NETWORK PLANNING: THE COVERAGE UNDER DAYTIME CONDITIONS FROM A NETWORK OF TRANSMITTERS ARRANGED IN A UNIFORM LATTICE

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Summary

The report collates definitions of the various types of network where transmitters are arranged geographically over an area and a given number of frequency channels is available for use. The method of calculation of the coverage is described and useful formulae stated. An exemplary tabulation, for limited ranges of power, frequency, ground conductivity and distance, is attached.

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Head of Research Department

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(RA-110)

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1. Introduction

The object of this report is to explain the nature of the different types of networks of transmitters, to assemble, for reference purposes, the more useful formulae relating to networks and to give examples of the calculation of coverage.

As a starting point in planning a new network of transmitters it is often useful to assess the area coverage that would be realised under uniform conditions and on the assumption that there are no restrictions on the siting of transmitters. This theoretical ideal coverage can then be used as a standard of comparison with actual practical schemes limited in choice of site and affected by differences in ground conductivity over the service area.

2. Groundwave services by day

The groundwave services are of particular importance because the public tends to use sound broadcasting services by day and television services during the evening.

The methods and calculations apply only to propagation over ground of uniform conductivity and for cases where the frequency channels envisaged for a particular network of stations are relatively close to each other so that propagation differences with frequency are relatively small. Clearly this is a very idealised case because in most countries (and particularly within the British Isles) quite large differences in ground conductivity may occur from point to point.[1] For the same reason the results are likely to be more useful for estimating coverage from networks of low-power transmitters, relatively closely spaced, rather than over a large continental area.

All coverage estimates are in terms of the proportion of an area that can be covered by a given number of transmitters. The results can be interpreted as giving a lowest estimate of population served because with practical planning the proportion of population served will always exceed the proportion of area served, sometimes by a very large factor.

3. Definitions

Various authors have considered the arrangement of transmitters sited at the intersection of two sets of parallel lines, each set having uniform spacing between its lines.[2,3,4,5,6] Except for the general case of Ref. 2, the analysis was until recent years applied to the television u.h.f. network planning, particularly for the Stockholm Plan of 1961. More recently[7] the principles have been applied to m.f. planning, as in this report.

4. Uniform and non-uniform networks

Using two sets of uniformly spaced parallel straight lines the lattice may be said to be uniform, forming uniform networks of transmitters. Fig. 1 is an example of this type. A non-uniform lattice would be one in which the lines forming it may be neither straight, parallel nor uniformly spaced. Fig. 2 being an example.[4]

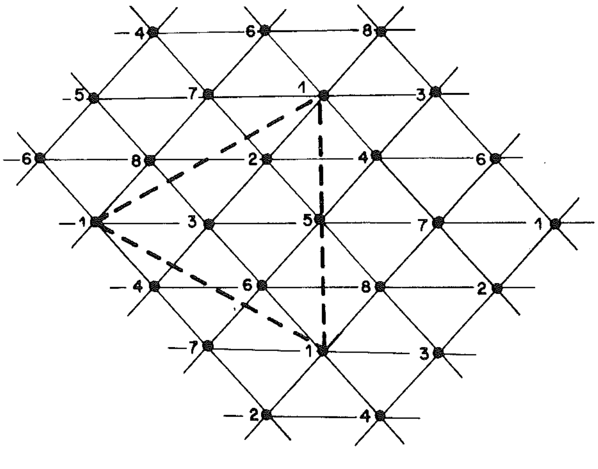

Fig. 1 - A uniform linear network for 8 channels

Non-uniform networks might have an application in cases where, for reasons of population distribution or propagation changes, it might be desirable to vary the density of transmitter sites in different parts of a country or large area.

This report does not consider non-uniform networks further.

5. Linear uniform network

A network is said to be linear when, as for example in Fig. 1, the differences between the channel numbers of successive sites is the same along *any* straight line joining any points of the lattice. Differences are taken as positive numbers, adding the total number of channels, N, to any

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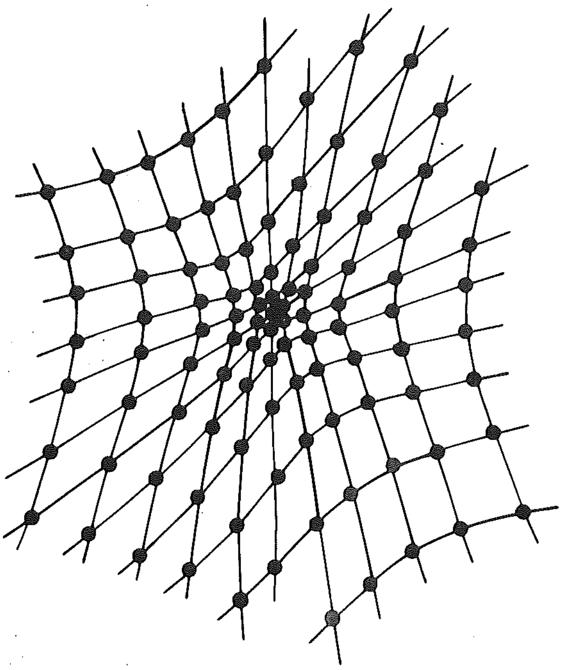

Fig. 2 - Non-uniform network

number if subtraction of the previous number in the line would give a negative result. e.g. (for 9 channels) a sequence would be 1, 4, 7, 1, 4, 7 etc.

For purposes of planning it is usual for the channel numbers to indicate the sequential order of the carrier frequency allocations, which would generally, though not essentially, be equally spaced in frequency.

Linear networks are of most importance when it is necessary to try to ensure that the users of any particular station, allotted a particular frequency channel, are equally affected, as regards various forms of mutual interference and the direction from which the interference is propagated, as the user of any other station on a different channel. Under conditions of complete uniformity of ground conductivity etc., the use of linear networks will therefore ensure equality of service area between the various transmitters in the network. This strictly applies only to an infinite network; clearly geographical boundaries will cause some inequality in service area.

6. Non-linear uniform network

Bearing in mind that population is seldom, if ever, uniformly distributed over a large area it is not always necessary to attempt uniformity of service area between transmitters. A non-linear network,^{5} i.e. one in which the channel number differences are not necessarily the same along the straight lines of the lattice, may have some advantages in particular cases, e.g. some pairs of stations occupying adjacent sites might occupy adjacent channels but not others, this situation sometimes being acceptable where a sparsely populated region intervenes in some parts of the whole area under consideration. Fig. 3, drawn to the same scale as Fig. 1, and for the same number of channels, shows a non-linear uniform distribution. The arrows indicate the direction in which maximum adjacent channel interference is propagated and it is seen that there is variation both in magnitude and direction from channel to channel, which would not be so in the case of a linear network.

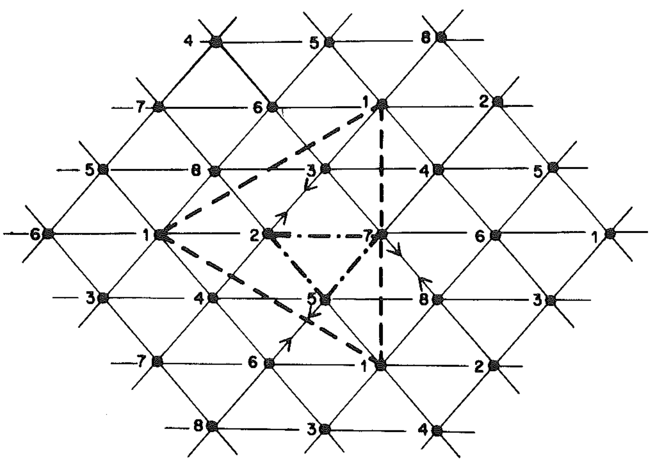

Fig. 3 - A non-linear network for 8 channels (equilateral co-channel distribution)

7. Equilateral site distribution network

This is represented by a lattice of equilateral triangles, each intersection representing the site of a transmitter. The lattice must be uniform, with the same spacing between the two sets of lines forming it and intersecting at 60°. Fig. 4 is an example of this case for a network of 10 channels and the network is linear, as defined above. In this case, for 10 channels, the lines joining the co-channel stations do not also form an equilateral triangle.

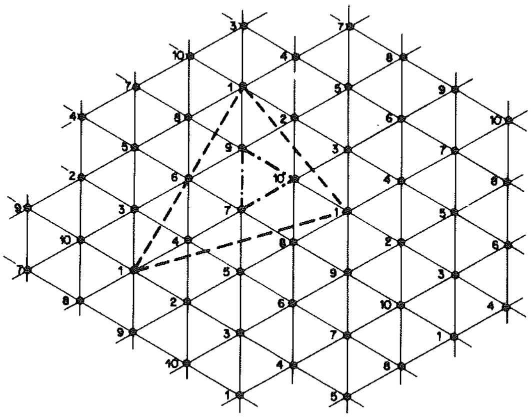

Fig. 4 - An equilateral site distribution linear network for 10 channels

8. Equilateral co-channel network

In this case the form of the lattice is such that when lines are drawn between sites using the same channel, then these lines form equilateral triangles. Under these conditions the 'elementary' triangles formed by lines joining adjacent transmitter sites may or may not also be equilateral. The distribution shown by the examples in Figs. 1 and 3 for 8 channels, shows the co-channel triangles, as shown by the dashed lines, as equilateral, whereas the elementary triangles joining adjacent sites are not.

9. Regular network

If lines joining the co-channel sites of a system form equilateral triangles and lines joining the adjacent sites of the same system *also* form equilateral triangles, the network is said to be regular. This will only occur[6] when the number of channels N, satisfies the condition $N = a^2 + b^2 + ab$ where a and b are any positive integers or either is zero. A tabulation of such numbers is given in Section 10 below and in Ref. 6. Fig. 5 is an example of a regular network for 9 channels and it should be noted that for this and some other numbers of channels, although regularity, as defined, can be achieved, the channel distribution is not linear. Linearity can only be achieved for this particular number of channels by a departure from regularity as shown in Figs. 6 and 7, the former arrangement providing linearity with equilateral site distribution and the latter giving linearity with equilateral co-channel distribution.

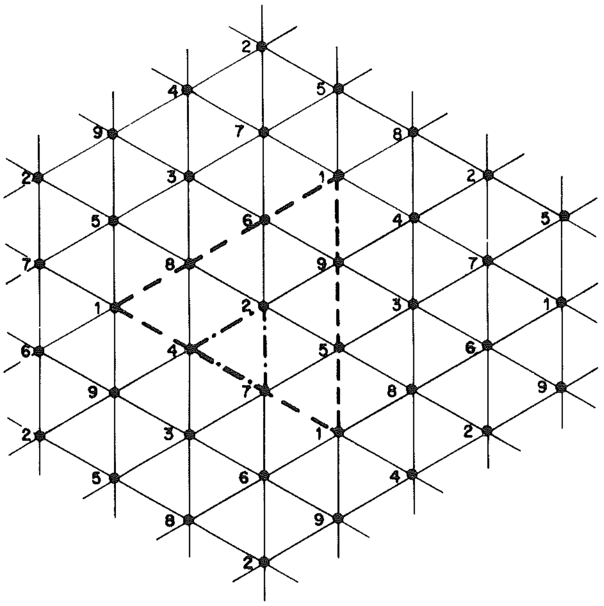

Fig. 5 - Regular network for 9 channels

10. Optimum network

A network which uses a site distribution and arrangement of the available channels in such a way that the greatest efficiency of coverage is obtained, may be said to be optimum. Efficiency of coverage implies that there is minimum overlap of the service areas of each of the transmitters and that the mutual interference of various kinds, such as co-channel, adjacent channel and image channel, has been minimised and is in general of equal level in each of the service areas.

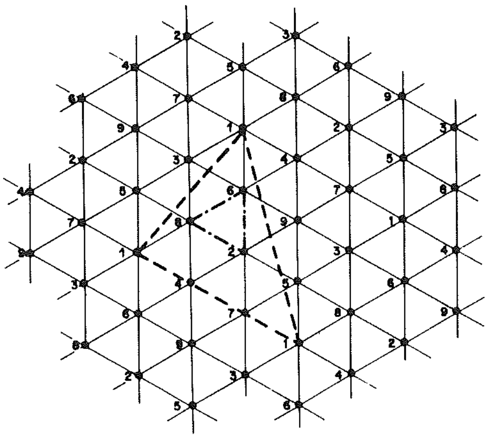

Fig. 6 - Linear network for 9 channels (equilateral site distribution)

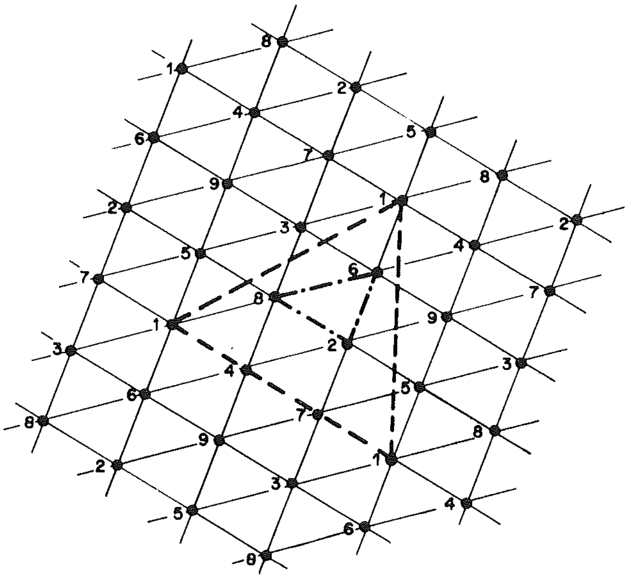

Fig. 7 - Linear network for 9 channels (equilateral co-channel distribution)

If a network is finite in extent and, as must be the case, uses a finite number of frequency channels, boundary effects and edge-of-band effects must to some extent unequalise the service areas of the transmitters sited near the boundaries of the area or using edge-of-band frequency channels.

To approach minimum overlap and equalisation of coverage the optimum network should, if possible, be made both regular and linear. Fig. 8 is an example of this case, shown for 7 channels.

The numbers of channels required for the formation of optimum networks, i.e. those both linear and regular,

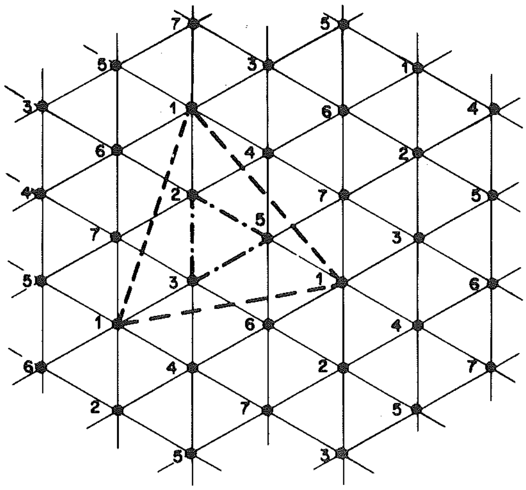

Fig. 8 - Optimum network for 7 channels (linear and regular)

are derived from the formula

$$N = a^2 + b^2 - ab$$

where (1) a and b are integers (zero excluded)

(2) a and b must have no common factor

(3) values for N must also be prime to 9 e.g. 7, 13, 19, etc.

Considering now networks which are regular or regular and linear (i.e. optimum) we are able to construct the following list of numbers of channels in which (for numbers up to 150) those that form optimum networks are underlined:

1, 3, 4, 7, 9, 12, 13, 16, 19, 21, 25, 27, 28, 31, 36, 37, 39, 43, 48, 49, 52, 57, 61, 63, 64, 67, 73, 75, 76, 79, 81, 84, 91, 93, 97, 100, 103, 108, 109, 111, 112, 117, 121, 124, 127, 129, 133, 139, 144, 147, 148

11. Calculation of groundwave coverage under idealised conditions

For this purpose it is assumed that the network will be a 'regular' network as defined above, with the lines joining the co-channel sites and the lines joining the adjacent sites both forming equilateral triangles.

Figs. 9 and 10 illustrate the meaning of the symbols used as defined below:

D = distance between the sites of co-channel stations in a regular equilateral network

r = service radius of each station. It can be either:

(a) the radial distance from each transmitting site to points where the field strength of the transmitter exceeds the combined field strengths from all other stations in the network by the required protection ratio, or

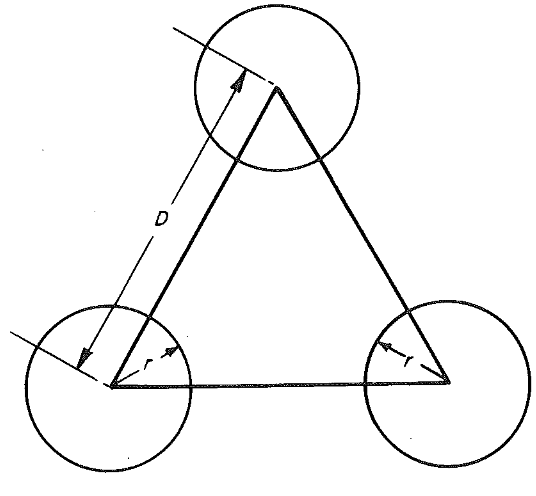

Fig. 9 - Co-channel distance and service radius in a network

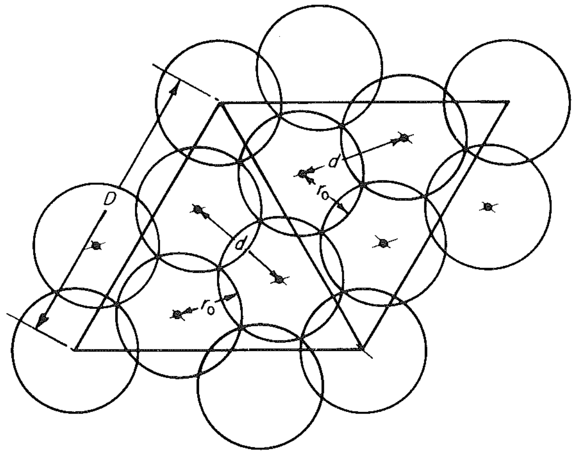

Fig. 10 - Full coverage of an area by a regular network (7 channels)

(b) the radial distance to points where the field strength falls to a value just sufficient to overcome man-made or atmospheric noise or some independent source of interference such as a distant transmission from a station not forming part of the network.

In case (a) r will be independent of the power of the transmitters and in case (b) r will increase with power.

In a theoretical paper[7] inter-station interference limits and noise-interference limits of service area are both taken into account and it will be clear that with relatively closely spaced co-channel stations noise will be less apparent than interference and vice-versa.

N = number of channels used in a 'regular' network = 1, 3, 4, 7, 9, 12, 13, 16 . . . etc.[6]

d = separation between adjacent sites in the whole network (Fig. 10)

r_0 = the value for the service radius r such that the whole area is just covered, with minimum possible overlap (see Fig. 10).

The following general relationships then apply:

$$D = \sqrt{N}\,d \qquad (1)$$

$$D = r_0\sqrt{3N} \qquad (2)$$

Formula 1 is not used to calculate the actual coverage given by a particular network, it gives simply the distance between the adjacent sites in relation to the distance between the co-channel transmitters.

Formula 2 is useful for determining whether the number of channels available will give full area coverage. If r is the service range of each station, calculated, for example, by the method given below in Section 13, then the number of channels will be sufficient for full coverage if $r_0 \leqq r$, the value of r_0 having been calculated by means of formula 2.

Conversely, to determine the minimum number of channels required to give full coverage, the 'regular' numbers 1, 3, 4, 7, etc. should be inserted in Equation 2 successively to find which number gives a value for r_0 just below r. This procedure implies however that the co-channel distance D has already been determined; this is discussed in the following Section 12.

An example of a simple tabulation leading to the choice of the number of channels required for full coverage is now given:

e.g. D (co-channel spacing = 230 km (say)
r (calculated service range) = 46 km (say)

N	$\sqrt{3N}$	$r_0 = \dfrac{D}{\sqrt{3N}}$
3	3	77 km
4	3·46	65·6 km
7	4·58	50·4 km
9	5·20	44·3
12	6·0	38·3

Thus minimum number of channels required = 9.

Note: Clearly if the requirements are *nearly* met by a lower number of channels it would be wasteful to employ the greater number theoretically required.

12. The co-channel separation distance D

Optimum values for this distance in the case of uniform networks can be determined by the methods given in Reference 7 (Eden and Minne) and the value will depend upon the required protection ratio, the power, frequency, ground conductivity σ and an agreed value for the 'noise limited' field strength, E_{min} which will clearly depend upon the degree of natural or man-made noise. The value of the optimum co-channel separation distance will also depend upon whether reception is to be by

(a) groundwave under daytime conditions
(b) groundwave under night-time conditions
or (c) indirect wave under night-time conditions.

The word 'optimum' here implies that the maximum percentage coverage will be achieved per channel in each case.

The following is a table indicating some variations of optimum values for D met with using a limited selection of the parameters listed above. These figures apply only to a protection ratio of 40 dB and are approximate.

The Eden-Minne paper[7] was particularly directed towards the problems of coverage by night and certain approximations were assumed to be valid.

The present report is concerned (Section 2 above) only with groundwave services by day and the results given in the Eden-Minne paper cannot accurately be extrapolated for cases where the transmitter powers are relatively low and where the protection ratios are considerably less than 40 dB. Computer methods are desirable in these cases, where multiple interference effects must be allowed for and where it cannot be assumed (as in the method used by Eden and Minne) that the interference levels are approximately the same at the site of the wanted transmitter as at any other point within the service area.

13. Estimation of the groundwave service range of one station in an equilateral co-channel network

Fig. 11 shows the location of typical receiving points

Condition	Power kW	Co-channel distance D for 500 kHz, σ = 3 mmho/m E_{min} = 67 dBμ	1500 kHz, σ = 1 mmho/m E_{min} = 58 dBμ
(a) groundwave – daytime	1	340 Kms	100 Kms
	30	520 Kms	180 Kms
	1000	820 Kms	320 Kms
(b) groundwave – night	1	2000 Kms	1200 Kms
	30	3500 Kms	1800 Kms
	1000	5300 Kms	2400 Kms
(c) indirect wave – night	1	No service (E_{min} not exceeded)	No service
	30	4500 Kms	4500 Kms
	1000	6500 Kms	6500 Kms

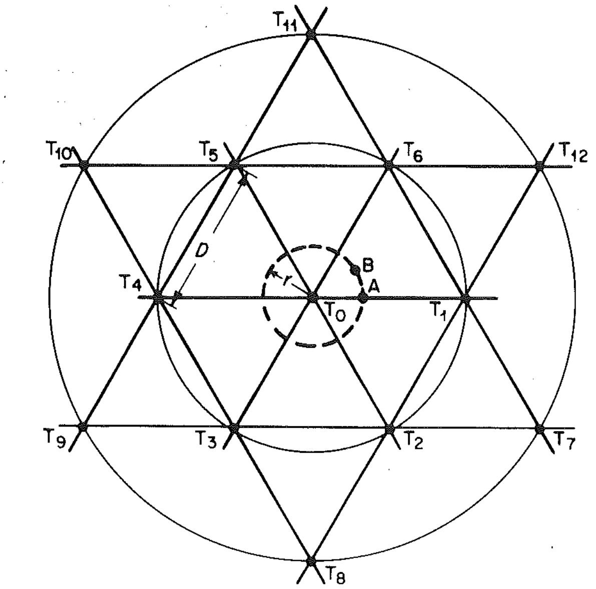

Fig. 11 - Service range of a transmitter in a co-channel network

(A and B) at the edge of the service area of a 'wanted' station in relation to the position of some other stations in the network. The figure shows the position of the interfering co-channel transmitters in the first two 'rings' of these transmitters. In an extensive network there will be many more 'rings' of interfering transmitters located at the intersections of the lines of the equilateral triangular lattice.*

By definition the service area of the 'wanted' station T_0 will be the region bounded by the dashed line (approximately a circle) at any point on which the field strength of the wanted station T_0 will exceed the combined field of the other transmitters by the amount of the required protection ratio. By the use of a computer it is possible to calculate the service radius r of the wanted transmitter T_0, allowing for the combined effects (on a power addition basis) of all the transmitters in any number of 'rings' of interfering transmitters. This radius r will vary very slightly with the position of the receiving point A along the boundary of the service area, as defined above, between the position where A lies directly between T_0 and T_1 and when the receiving point is at position B, the direction T_0B making an angle of 30° with the line T_0T_1.

We are here concerned with groundwave propagation in the idealised case of uniformly conducting ground (not sea, as a network of transmitters with sea paths between is improbable). It will be seen that the major sources of interference to a receiving point such as A in Fig. 11 are the transmitters T_1, T_2 and T_6 particularly if a fairly low protection ratio is acceptable, making r a significant proportion of the co-channel distance D. In the case of a receiver at position B under similar conditions the major sources of interference will be transmitters T_1 and T_6. Because of the increased distance, the second and subsequent rings of interfering transmitters often will not contribute a significant amount to the combined interference of the nearest transmitters in the first ring.

14. Applications

If a low protection ratio is acceptable, as for example 10 dB in the case of a synchronised network of common programme transmitters, the service radius r will be sufficiently accurately calculated if we take account of the combined interference from transmitters T_1, T_2 and T_6 only; taking the combined field E as

$$E = \sqrt{E_1^2 + 2E_2^2}$$

where E_1 is the field strength at distance $D - r$ from transmitter T_1

and E_2 is the field strength at distance $\sqrt{D^2 + r^2 - Dr}$ from transmitters T_2 and T_6.

The computer can be programmed to calculate r for various co-channel distances D and for a given protection ratio and the use of this approximation will save some computer time.

However, if the protection ratio required is relatively high, say 30 dB or 40 dB as for the case of a co-channel network with transmitters radiating different programmes, r may be small compared with D and a significant contribution of interference may arise from all the 6 transmitters in the first ring and even from some or all the transmitters in the second ring, e.g. T_7 and T_{12} in Fig. 11. Under some conditions such as relatively close spacing of the co-channel station combined with high ground conductivity and the use of a frequency in the lower part of the band it may well be necessary to take into account the contributions of interference from transmitters in the 2nd, 3rd, or even rings of higher order. In this report however, only the contributions from the 1st and 2nd rings has been considered for the numerical examples (see Section 18).

15. Geometry of equilateral co-channel network

The following simple formulae give the distances of the two typical receiving points at A and B (see Fig. 11) from the 6 transmitters in the first ring contributing effectively to the total interference.

Let D = co-channel spacing in regular equilateral network
r = distance of receiver from wanted transmitter at 0 (see Fig. 11)

Then if receiver is at position A

Distance from T_1 $= D - r$

T_2 and T_6 $= \sqrt{D^2 + r^2 - Dr}$

T_3 and T_5 $= \sqrt{D^2 + r^2 + Dr}$

T_4 $= D + r$

---

* See, for example, Table II.

If receiver is at position B

Distance from T_1 and $T_6 = \sqrt{D^2 + r^2 - 3Dr}$

T_2 and $T_5 = \sqrt{D^2 + r^2}$

T_3 and $T_4 = \sqrt{D^2 + r^2 + 3Dr}$

Also, if the receiver is at position A and is using a loop aerial correctly oriented towards the transmitter at T_0, the following reduction factors resulting from the cosine law aerial pattern may also be taken into account. As regards reception (interference) from transmitters T_1 and T_4, reduction factor = 1·0. As regards reception (interference) from transmitters T_2 and T_6

$$\text{reduction factor} = \frac{D - 2r}{2\sqrt{D^2 + r^2 - Dr}}$$

As regards reception (interference) from transmitters T_3 and T_5

$$\text{reduction factor} = \frac{D + 2r}{2\sqrt{D^2 + r^2 + Dr}}$$

Similarly, if the receiver is at position B, the following reduction factors will apply.

As regards interference from T_1 and T_6

$$\text{reduction factor} = \frac{\sqrt{3}D - 2r}{2\sqrt{D^2 + r^2 - \sqrt{3}Dr}}$$

As regards interference from T_2 and T_5

$$\text{reduction factor} = \frac{r}{\sqrt{D^2 + r^2}}$$

As regards interference from T_3 and T_4

$$\text{reduction factor} = \frac{\sqrt{3}D + 2r}{2\sqrt{D^2 + r^2 + \sqrt{3}Dr}}$$

There is some doubt whether the loop receiving aerial reduction factors should be taken into account because most receivers with this type of aerial are used in indoor situations where the fields of the wanted and unwanted station are likely to be considerably distorted by the presence of house wiring etc. In computing service areas or percentage coverage on a conservative basis it is probably best to omit these factors from the calculation. This has been done in the case of the examples appended to this report.

16. Area coverage for a single channel

Referring to Fig. 9 it will be seen that if the whole area is considered to be made up of a series of equilateral triangles the contribution of service of each station to each triangle is $\pi r^2/6$ from which it can be shown that the ratio of the area covered to the whole area is

$$\frac{2\pi}{\sqrt{3}} \cdot \frac{r^2}{D^2} \quad \text{or} \quad 362\cdot8\frac{r^2}{D^2}\ \%$$

The limit of validity of this formula is reached when $r = D/2$, i.e. when the service areas just meet but do not overlap. Clearly in the case of a single channel this condition never arises because at this point the protection ratio would be zero.

17. Area coverage of network using several channels

The overall percentage coverage for a network of N channels (involving equilateral co-channel networks) can also be calculated by the multiplication by N of the single channel coverage *provided* that the service ranges are such that no overlapping occurs, i.e. when $r < d/2$ the limit in these cases being 90·7% (circles of equal radius touching but not overlapping.

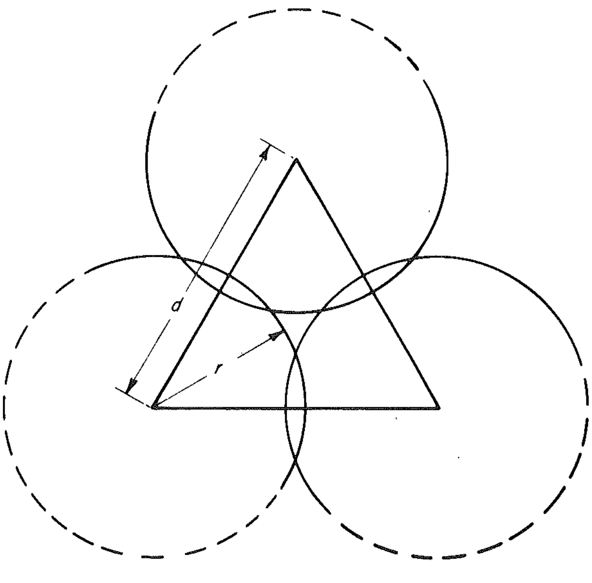

Fig. 12 - Special case of overlapping service areas

On occasion it may be required to calculate the percentage area coverage where the actual dimensions are such that the service radius r is greater than half the distance between adjacent sites, i.e. where some overlapping occurs, as shown in Fig. 12, but not a sufficient overlap to provide 100% area coverage as for the limiting case of $r = d/\sqrt{3}$.

The relevant formula is:

$$C\ \text{(area coverage, \%)} = \frac{\frac{\pi}{2} - 3\theta + \frac{3}{2}\sin 2\theta}{3\cos^2\theta} \times 100$$

where $\theta = \cos^{-1}\dfrac{d}{2r}$ expressed in radians

Example:–

$$d = 100 \text{ kms}$$

$$r = 54 \text{ kms}$$

Therefore $\cos\theta = \dfrac{d}{2r} = 0{\cdot}962$

$$\theta = 15{\cdot}93^\circ = 0{\cdot}278 \text{ radians}$$

$$\sin^2\theta = 0{\cdot}528$$

$$\cos^2\theta = 0{\cdot}925$$

Substitution of these values in the formula above for C gives $C = 96{\cdot}05\%$.

18. Results for typical co-channel networks (computer output)

Table I, appended on the following pages, shows the results as computed area coverages (%), for three m.f. frequencies, two values of ground conductivity σ and four values of protection ratio, for various values of co-channel site separation in an equilateral co-channel network. Results are given for two values only of transmitter radiated power, viz. 1 kW and 10 W. The Research Department Elliott 803 computer was not available for long enough for results to be produced for other values of transmitter radiated power or for higher values of ground conductivity than σ = 3 mmho/m.

The service range r is the distance from the wanted transmitter at which the wanted field E_w is attained, using the following formula to calculate E_w.

$$E_w = \sqrt{A^2\Sigma(E_1^2 + E_2^2 + E_3^2 + \ldots E_{12}^2) + 10{,}000E_n^2}$$

Where A = the required protection ratio against the combined interferences from the twelve transmitters in the first and second adjacent rings (see Fig. 11). In the tabulated results four values of the protection ratio A have been considered, viz. 40 dB, 30 dB, 20 dB and 10 dB. The first two of these can be taken to give reasonable and just acceptable limits of interference respectively, with different programmes radiated from all the transmitters radiated in the network, the third value, 20 dB, would be quite unacceptable but the fourth value, 10 dB, represents a reasonable value of protection when a *common* programme is radiated from the transmitters in the network.

The value E_n is the noise field strength, which when multiplied by the appropriate protection ratio, gives the values of 'noise limited field strength' (see Ref. 7), which in Section 12 of this Report has been referred to as E_{min}. For the purpose of the tabulated examples of coverage given here we have taken the same three typical values of E_{min} as those used in the Eden and Minne paper,[7] viz. 67 dBμ (2·3 mV/m) at 500 kHz, 61 dBμ (1·1 mV/m) at 1000 kHz and 58 dBμ (0·8 mV/m) at 1500 kHz.

Where we are concerned with lower values of protection ratio A we have assumed, until such time as the results of any subjective tests on the relative annoyance of interfering r.f. signals and noise may become available, that a protection of 40 dB shall, in all cases, be required against the RMS level of interfering noise, which is itself frequency dependent. That it is necessary to make some such assumption is clearly apparent where an r.f. protection ratio against other signals as low as 10 dB can be accepted (common programme working) whereas in this latter case a wanted signal/noise ratio of 10 dB would be quite unacceptable. In the formula above the significance of the numerical value 10,000 in the second term is that it is the square of 100 (protection ratio 40 dB).

In the case of all networks of co-channel transmitters it will be clear that when the stations are closely spaced the service range of each station is determined predominantly by the combined interference from the others in the network whereas with wide spacing of the sites the noise predominates and the interfering signals tend to have a negligible effect.

19. Choice of the network parameters (power, co-channel spacing) to give the best coverage

Examination of a set of tables such as Table I attached on pages 9 – 16 (which cover a limited range of powers and conductivity values) will, in general, reveal an 'optimum value' for the percentage *area* coverage C%, in terms of co-channel separation distance and radiated powers. If the population were uniformly distributed over the whole area to be covered it would then be easy to decide the best values for the radiated powers and co-channel separation distance for a given known ground conductivity, it being assumed that for international planning reasons there was no choice of frequency. Having done this the number of channels required for full coverage could then be determined by the method given in Section 11, using the values of D and r taken from the tables. It is highly likely that if a high protection ratio were required, with separate programmes radiated from each station, an insufficient number of channels would be available to provide full coverage.

Under practical conditions, fortunately for service planning of this kind, the population is not uniformly distributed but tends to be grouped into 'conurbations' of one kind or another. Accepting the impossibility of full 'area' coverage we can now aim at a maximum percentage population coverage and the following procedures are suggested.

Using a population density map, or a specially prepared map showing the position of the centres of towns or conurbations exceeding a certain minimum population (say, for example, 20,000 inhabitants), a uniform lattice of parallel straight lines intersecting at 60° is roughly fitted to the map so that all the marked positions of the population

TABLE I

Service range and percent coverage per channel for 1 kW radiated

Signal protection ratio 40 dB

Frequency 500 kHz

	σ = 3 mmho/m			σ = 1 mmho/m		
D_{kms}	r_{kms}	$C\%$	A_{eff}	r_{kms}	$C\%$	A_{eff}
20	0·12	< 0·1	40	0·28	0·1	40
40	0·37	< 0·1	40	1·11	0·3	40
60	0·85	0·1	40	2·72	0·7	40
80	1·52	0·1	40	4·65	1·2	40
100	2·49	0·2	40	6·69	1·6	40
150	6·67	0·7	40	12·2	2·4	40
200	12·6	1·4	40	17·9	2·9	40
250	20·1	2·4	40	22·3	2·9	40
300	28·3	3·2	40	25·0	2·5	40

Frequency 1000 kHz

20	0·38	0·1	40	0·92	0·8	40
40	1·66	0·6	40	2·75	1·7	40
60	3·54	1·3	40	4·48	2·0	40
80	5·66	1·8	40	6·29	2·2	40
100	7·86	2·2	40	8·15	2·4	40
150	14·0	3·2	40	13·1	2·8	40
200	20·6	3·9	40	16·5	2·5	40
250	26·7	4·1	40	17·7	1·8	40
300	30·3	3·7	40	18·0	1·3	40

Frequency 1500 kHz

20	0·78	0·6	40	1·3	1·5	40
40	2·71	1·7	40	2·83	1·8	40
60	4·66	2·2	40	4·60	2·1	40
80	6·60	2·5	40	6·45	2·4	40
100	8·74	2·8	40	8·35	2·5	40
150	14·6	3·4	40	12·1	2·4	40
200	20·2	3·7	40	13·6	1·7	40
250	23·1	3·1	40	13·8	1·1	40
300	24·2	2·4	40	13·9	0·8	40

Explanation of symbols

D_{kms} – Co-channel site separation in kilometres

r_{kms} – Service range of each transmitter in kilometres

$C\%$ – Percentage area coverage for one channel

A_{eff} – Effective protection ratio, i.e.

$$\frac{E_w}{\sqrt{\Sigma(E_1^2 + E_2^2 + E_3^2 + \ldots . E_{12}^2) + E_n^2}}$$

where E_w is the 'wanted' field strength calculated from the formula given on page 8 and E_n is the RMS noise field strength appropriate to the frequency given.

TABLE I (Cont.)

Service range and percent coverage per channel for 1 kW radiated

Signal protection 30 dB

	σ = 3 mmho/m			σ = 1 mmho/m		
D_{kms}	r_{kms}	$C\%$	A_{eff}	r_{kms}	$C\%$	A_{eff}
Frequency 500 kHz						
20	0·38	0·1	30	0·85	0·7	30
40	1·19	0·3	30	3·07	2·1	30
60	2·49	0·6	30	6·42	4·1	30
80	4·49	1·1	30	9·73	5·4	30·1
100	7·18	1·9	30	13·0	6·2	30·2
150	16·0	4·1	30·2	20·3	6·6	31·5
200	26·1	6·2	30·6	24·5	5·4	34·3
250	35·5	7·3	31·6	26·0	3·9	37·2
300	42·0	7·1	33·6	26·5	2·8	39·0
Frequency 1000 kHz						
20	1·10	1·1	30	2·02	3·7	30
40	4·04	3·7	30	5·02	5·7	30
60	7·41	5·5	30	7·88	6·3	30·1
80	10·9	6·7	30·1	10·7	6·5	30·4
100	14·3	7·4	30·2	13·4	6·5	31·2
150	22·8	8·4	31	17·1	4·7	35·1
200	29·0	7·6	33·5	18·1	3·0	38·4
250	31·4	5·7	36·8	18·2	1·9	39·6
300	32·1	4·1	39·0	18·3	1·4	39·9
Frequency 1500 kHz						
20	1·92	3·4	30	2·37	5·1	30
40	5·21	6·2	30	5·18	6·1	30
60	8·23	6·8	30·1	7·94	6·4	30·3
80	11·4	7·4	30·2	10·4	6·1	31·2
100	14·6	7·7	30·5	12·1	5·3	32·9
150	21·2	7·2	32·7	13·7	3·0	37·6
200	23·7	5·1	36·9	14·0	1·8	39·5
250	24·3	3·4	39·2	14·0	1·1	39·9
300	24·2	2·4	29·8	13·9	0·8	$\cong$ 40·0

Explanation of symbols

D_{kms} – Co-channel site separation in kilometres

r_{kms} – Service range of each transmitter in kilometres

$C\%$ – Percentage area coverage for one channel

A_{eff} – Effective protection ratio, i.e.

$$\frac{E_w}{\sqrt{\Sigma(E_1^2 + E_2^2 + E_3^2 + \dots . E_{12}^2) + E_n^2}}$$

where E_w is the 'wanted' field strength calculated from the formula given on page 8 and E_n is the RMS noise field strength appropriate to the frequency given.

TABLE I (Cont.)

Service range and percent coverage per channel for 1 kW radiated

Signal protection ratio 20 dB

Frequency 500 kHz

	σ = 3 mmho/m			σ = 1 mmho/m		
D_{kms}	r_{kms}	$C\%$	A_{eff}	r_{kms}	$C\%$	A_{eff}
20	1·16	1·2	20	2·37	5·1	20
40	3·50	2·8	20	6·97	11·0	20·1
60	7·06	5·0	20	12·3	15·2	20·2
80	11·5	7·5	20·1	16·9	16·2	20·8
100	16·7	10·2	20·2	20·8	15·6	21·9
150	30·1	14·6	21	25·6	10·5	27·2
200	40·3	14·8	23·3	26·5	6·4	32·9
250	45·0	11·8	27·3	26·7	4·1	36·8
300	46·7	8·8	31·7	26·8	2·9	38·8

Frequency 1000 kHz

20	2·84	7·3	20	3·8	13·1	20
40	7·91	14·2	20	8·46	16·2	20·2
60	13·3	17·8	20·1	12·9	16·7	21·1
80	18·2	18·9	20·4	15·7	14·0	22·3
100	22·8	18·9	21·1	17·1	10·7	26·4
150	30·0	14·5	25·4	18·1	5·3	34
200	31·9	9·2	31·5	18·3	3·0	38·2
250	32·3	6·1	36·3	18·2	1·9	39·6
300	32·4	4·2	38·8	18·3	1·4	39·9

Frequency 1500 kHz

20	3·82	13·2	20	4·13	15·5	20
40	8·93	18·1	20·1	8·61	16·8	20·6
60	13·6	18·7	20·3	11·7	13·9	22·7
80	17·9	18·1	21·3	13·2	9·8	26·4
100	20·9	15·9	23·2	13·7	6·8	30·4
150	23·8	9·1	30·4	14·0	3·2	37·3
200	24·3	5·4	36·4	14·0	1·8	39·5
250	24·3	3·4	39	14·0	1·1	39·9
300	24·5	2·4	39·8	13·9	0·8	40

Explanation of symbols

D_{kms} — Co-channel site separation in kilometres

r_{kms} — Service range of each transmitter in kilometres

$C\%$ — Percentage area coverage for one channel

A_{eff} — Effective protection ratio, i.e.

$$\frac{E_w}{\sqrt{\Sigma(E_1^2 + E_2^2 + E_3^2 + \ldots . E_{12}^2) + E_n^2}}$$

where E_w is the 'wanted' field strength calculated from the formula given on page 8 and E_n is the RMS noise field strength appropriate to the frequency given.

TABLE I (Cont.)

Service range and percent coverage per channel for 1 kW radiated

Signal protection ratio 10 dB

Frequency 500 kHz

	σ = 3 mmho/m			σ = 1 mmho/m		
D_{kms}	r_{kms}	$C\%$	A_{eff}	r_{kms}	$C\%$	A_{eff}
20	3·41	10·5	10	5·38	26·3	10
40	9·16	19·0	10	12·5	35·3	10·2
60	16·0	25·9	10·1	19·0	36·2	11·2
80	23·2	30·4	10·4	23·6	31·7	14
100	30·0	32·7	10·9	25·6	23·8	17·7
150	42·1	28·6	14·6	26·6	11·4	26·4
200	46·4	19·5	20·6	26·7	6·4	32·7
250	47·2	13·0	26·4	26·7	4·1	36·8
300	47·3	9·0	31·4	26·8	2·9	38·8

Frequency 1000 kHz

20	5·85	31·0	10	6·36	36·7	10
40	13·3	39·9	10·1	13·0	38·3	11·2
60	20·7	43·0	10·7	16·8	28·6	15·5
80	26·4	39·4	12·4	17·9	18·1	20·7
100	29·8	32·3	15·3	18·1	11·9	25·4
150	32·2	16·7	24	18·2	5·4	33·9
200	32·3	9·5	31·3	18·3	3·0	38·2
250	32·3	6·1	36·3	18·2	1·9	39·5
300	32·4	4·2	38·8	18·3	1·4	39·9

Frequency 1500 kHz

20	6·47	38·8	10	6·73	41·1	10·2
40	13·5	41·5	10·4	12·1	33·1	13·3
60	19·8	39·4	12·2	13·6	18·7	19·6
80	22·8	29·4	16	13·9	10·9	25·4
100	23·8	20·5	20·5	13·9	7·0	30·1
150	24·2	9·5	30	14·0	3·2	36·4
200	24·3	5·4	36·3	14·0	1·8	39·5
250	24·3	3·4	39·1	14·0	1·1	39·9
300	24·5	2·4	39·8	13·9	0·8	40

Explanation of symbols

D_{kms} – Co-channel site separation in kilometres

r_{kms} – Service range of each transmitter in kilometres

$C\%$ – Percentage area coverage for one channel

A_{eff} – Effective protection ratio, i.e.

$$\frac{E_w}{\sqrt{\Sigma(E_1^2 + E_2^2 + E_3^2 + \ldots . E_{12}^2) + E_n^2}}$$

where E_w is the 'wanted' field strength calculated from the formula given on page 8 and E_n is the RMS noise field strength appropriate to the frequency given.

TABLE I (Cont.)

Service range and percent coverage per channel for 10W radiated

Signal protection ratio 40 dB

Frequency 500 kHz

	σ = 3 mmho/m			σ = 1 mmho/m		
D_{kms}	r_{kms}	$C\%$	A_{eff}	r_{kms}	$C\%$	A_{eff}
20	0·12	0·0	40	0·28	0·1	40
40	0·37	0·0	40	1·11	0·3	40
60	0·85	0·1	40	2·67	0·7	40
80	1·52	0·1	40	4·26	1·0	40
100	2·49	0·2	40	5·62	1·1	40
150	5·93	0·6	40	7·25	0·8	40
200	8·69	0·7	40	7·52	0·5	40
250	10·1	0·6	40	7·69	0·3	40
300	10·4	0·4	40	7·47	0·2	40
Frequency 1000 kHz						
20	0·38	0·1	40	0·92	0·8	40
40	1·66	0·6	40	2·71	1·7	40
60	3·49	1·2	40	4·13	1·7	40
80	5·43	1·7	40	5·04	1·4	40
100	7·18	1·9	40	5·52	1·1	40
150	9·59	1·5	40	5·79	0·5	40
200	10·3	1·0	40	5·76	0·3	40
250	10·4	0·6	40	5·74	0·2	40
300	10·4	0·4	40	5·71	0·1	40
Frequency 1500 kHz						
20	0·79	0·6	40	1·3	1·5	40
40	2·71	1·7	40	2·71	1·7	40
60	4·54	2·1	40	3·84	1·5	40
80	6·05	2·1	40	4·34	1·1	40
100	7·08	1·8	40	4·44	0·7	40
150	7·98	1·0	40	4·61	0·3	40
200	8·11	0·6	40	4·59	0·2	40
250	8·18	0·4	40	4·52	0·1	40
300	8·06	0·3	40	4·54	0·1	40

Explanation of symbols

D_{kms} – Co-channel site separation in kilometres

r_{kms} – Service range of each transmitter in kilometres

$C\%$ – Percentage area coverage for one channel

A_{eff} – Effective protection ratio, i.e.

$$\frac{E_w}{\sqrt{\Sigma(E_1^2 + E_2^2 + E_3^2 + \ldots . E_{12}^2) + E_n^2}}$$

where E_w is the 'wanted' field strength calculated from the formula given on page 8 and E_n is the RMS noise field strength appropriate to the frequency given.

TABLE I (Cont.)

Service range and percent coverage per channel for 10W radiated

Signal protection ratio 30 dB

Frequency 500 kHz

	σ = 3 mmho/m			σ = 1 mmho/m		
D_{kms}	r_{kms}	$C\%$	A_{eff}	r_{kms}	$C\%$	A_{eff}
20	0·38	0·1	30	0·85	0·7	30
40	1·19	0·3	30	2·95	2·0	30·3
60	2·49	0·6	30·1	5·48	3·0	31·8
80	4·26	1·0	30·5	6·76	2·6	34·3
100	6·20	1·4	31·2	7·28	1·9	36·7
150	9·59	1·5	34·9	7·54	0·9	39·3
200	10·4	1·0	38·1	7·52	0·5	39·8
250	10·6	0·7	39·4	7·69	0·3	39·9
300	10·7	0·5	39·8	7·47	0·2	40
Frequency 1000 kHz						
20	1·1	1·1	30	2·02	3·7	30·1
40	4·0	3·6	30·2	4·47	4·5	31·8
60	6·88	4·8	31·1	5·42	3·0	35·3
80	8·79	4·4	33	5·66	1·8	37·9
100	9·72	3·4	35·4	5·71	1·2	39·2
150	10·3	1·7	39	5·79	0·5	39·9
200	10·3	1·0	39·8	5·76	0·3	40
250	10·4	0·6	39·9	5·74	0·2	40
300	10·4	0·4	40	5·71	0·1	40
Frequency 1500 kHz						
20	1·92	3·4	30	2·33	4·9	30·3
40	4·98	5·6	30·6	4·0	3·6	33·6
60	6·94	4·9	32·8	4·42	2·0	37·5
80	7·7	3·4	35·8	4·49	1·1	39·2
100	7·96	2·3	37·9	4·54	0·7	39·7
150	8·13	1·1	39·7	4·61	0·3	40
200	8·11	0·6	39·9	4·59	0·2	40
250	8·18	0·4	39·9	4·52	0·1	40
300	8·06	0·3	40	4·54	0·1	40

Explanation of symbols

D_{kms} – Co-channel site separation in kilometres

r_{kms} – Service range of each transmitter in kilometres

$C\%$ – Percentage area coverage for one channel

A_{eff} – Effective protection ratio, i.e.

$$\frac{E_w}{\sqrt{\Sigma(E_1^2 + E_2^2 + E_3^2 + \ldots . E_{12}^2) + E_n^2}}$$

where E_w is the 'wanted' field strength calculated from the formula given on page 8 and E_n is the RMS noise field strength appropriate to the frequency given.

TABLE I (Cont.)

Service range and percent coverage per channel for 10W radiated

Signal protection ratio 20 dB

Frequency 500 kHz

	σ = 3 mmho/m			σ = 1 mmho/m		
D_{kms}	r_{kms}	$C\%$	A_{eff}	r_{kms}	$C\%$	A_{eff}
20	1·16	1·2	20	2·33	4·9	20·2
40	3·38	2·6	20·3	5·8	7·6	22·5
60	6·18	3·9	21·3	7·24	5·3	28·1
80	8·48	4·1	23·5	7·54	3·2	32·9
100	9·72	3·4	26·5	7·57	2·1	36·1
150	10·6	1·8	33·9	7·54	0·9	39·2
200	10·6	1·0	37·9	7·52	0·5	39·8
250	10·6	0·7	39·4	7·69	0·3	39·9
300	10·7	0·5	39·8	7·47	0·2	40

Frequency 1000 kHz

20	2·82	7·2	20	3·62	11·9	20·8
40	7·25	11·9	21·4	5·57	7·0	28
60	9·58	9·2	25·9	5·77	3·4	34·3
80	10·1	5·8	30·7	5·74	1·9	37·7
100	10·3	3·9	34·5	5·81	1·2	39·1
150	10·3	1·7	38·9	5·79	0·5	39·9
200	10·4	1·0	39·8	5·76	0·3	40
250	10·4	0·6	39·9	5·74	0·2	40
300	10·4	0·4	40	5·71	0·1	40

Frequency 1500 kHz

20	3·76	12·8	20·2	3·62	11·9	22·4
40	7·21	11·8	24·1	4·47	4·5	31·8
60	7·94	6·4	30·3	4·54	2·1	37·1
80	8·09	3·7	34·9	4·57	1·2	39·1
100	8·06	2·4	37·7	4·54	0·7	39·7
150	8·13	1·1	39·7	4·61	0·3	40
200	8·11	0·6	39·9	4·59	0·2	40
250	8·18	0·4	40	4·52	0·1	40
300	8·06	0·3	40	4·54	0·1	40

Explanation of symbols

D_{kms} – Co-channel site separation in kilometres

r_{kms} – Service range of each transmitter in kilometres

$C\%$ – Percentage area coverage for one channel

A_{eff} – Effective protection ratio, i.e.

$$\frac{E_w}{\sqrt{\Sigma(E_1^2 + E_2^2 + E_3^2 + \ldots . E_{12}^2) + E_n^2}}$$

where E_w is the 'wanted' field strength calculated from the formula given on page 8 and E_n is the RMS noise field strength appropriate to the frequency given.

TABLE I (Cont.)

Service range and percent coverage per channel for 10W radiated

Signal protection ratio 10 dB

Frequency 500 kHz

	σ = 3 mmho/m			σ = 1 mmho/m		
D_{kms}	r_{kms}	$C\%$	A_{eff}	r_{kms}	$C\%$	A_{eff}
20	3·31	9·9	10·3	4·89	21·7	11·4
40	7·48	12·7	12·3	7·32	12·2	19·3
60	9·7	9·5	16·5	7·59	5·8	27·5
80	10·4	6·2	21·2	7·62	3·3	32·8
100	10·6	4·1	25·6	7·57	2·1	3 ·61
150	10·8	1·9	33·7	7·54	0·9	39·2
200	10·6	1·0	38	7·52	0·5	39·8
250	10·6	0·7	39·3	7·69	0·3	39·9
300	10·7	0·5	39·8	7·47	0·2	40

Frequency 1000 kHz

D_{kms}	r_{kms}	$C\%$	A_{eff}	r_{kms}	$C\%$	A_{eff}
20	5·63	28·8	10·6	5·15	24·0	14·3
40	9·67	21·2	16·5	5·76	7·5	27·4
60	10·3	10·7	24·7	5·77	3·4	34·2
80	10·4	6·1	30·4	5·82	1·9	37·6
100	10·4	3·9	34·4	5·81	1·2	39·1
150	10·3	1·7	38·9	5·79	0·5	39·9
200	10·4	1·0	39·8	5·76	0·3	40
250	10·4	0·6	39·9	5·74	0·2	40
300	10·4	0·4	40	5·71	0·1	40

Frequency 1500 kHz

D_{kms}	r_{kms}	$C\%$	A_{eff}	r_{kms}	$C\%$	A_{eff}
20	6·03	32·9	11·6	4·4	17·6	18·9
40	7·99	14·5	22·2	4·55	4·7	31·5
60	8·12	6·6	29·9	4·54	2·1	37·1
80	8·09	3·7	34·9	4·57	1·2	39
100	8·15	2·4	37·6	4·54	0·7	39·7
150	8·13	1·1	39·7	4·61	0·3	40
200	8·11	0·6	39·9	4·59	0·2	40
250	8·18	0·4	40	4·52	0·1	40
300	8·06	0·3	40	4·54	0·1	40

Explanation of symbols

D_{kms} – Co-channel site separation in kilometres

r_{kms} – Service range of each transmitter in kilometres

$C\%$ – Percentage area coverage for one channel

A_{eff} – Effective protection ratio, i.e.

$$\frac{E_w}{\sqrt{\Sigma(E_1^2 + E_2^2 + E_3^2 + \dots . E_{12}^2) + E_n^2}}$$

where E_w is the 'wanted' field strength calculated from the formula given on page 8 and E_n is the RMS noise field strength appropriate to the frequency given.

centres lie at points of intersection of the lattice. The length of the sides of the equilateral triangles forming the lattice will then give the value of d (site separation distance), as defined in Section 11.

At this point it will be necessary to assume a value for N, the number of available channels and a starting point would be to take, successively, values for N of 1, 3 and 7 (giving optimum networks – see Section 10) and for each value to calculate the co-channel separation distance from the formula (1) on page 5 viz. $D = \sqrt{N}.d$. Use of the tables, for the given conductivity and frequency and the required protection ratio will then show what service range r is obtained and by comparison what is the optimum radiated power. An alternative approach would be to decide what was the required service range, then to decide by inspection of the tables what was the necessary co-channel separation distance and optimum radiated power and then the number of channels necessary to achieve this by the use of the formula $D = \sqrt{N}.d$.

20. Conclusion

This report is incomplete as it stands since the computed table of service range and area coverage at present only covers two rather extreme values of transmitted radiated power and only two values of ground conductivity. The purpose of the report is that it should be an aid to understanding methods of planning a groundwave daylight service for a large number of small stations for purposes such as local broadcasting. Extended computer programmes could be developed to calculate actual population coverages from networks of various dimensions applied to the United Kingdom, using the available data bank of population enclosed within squares of 0·5 km side over the whole country.

Computer methods could also be established to select the number of interfering transmitters in the surrounding rings to be taken into account in calculating the approximate service range of the 'wanted' station; to achieve a given accuracy, more interfering transmitters will have to be allowed for where the frequency is low, the ground conductivity high, and the co-channel spacing smaller than is the case when the frequency is high, the conductivity low and the co-channel spacing large.

It has been pointed out that in the case of large networks, under daylight conditions, the only reason for neglecting the effects of the more distant interfering transmitters is that, due to ground attenuation, their individual field strengths fall off more rapidly than on an 'inverse distance' ($1/R$) basis. Since the number of transmitters within an annulus of mean radius R tends to increase proportionally with the value of R, summation of the interference effects out to a large distance would give a divergent result but for the over-riding effect of ground attenuation.

Should groundwave coverage of a large network of low powered transmitters at night be investigated it will be necessary to bear in mind the fact that many more successive rings of interfering transmitters may contribute substantially to the mean interference at any point.

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21. References

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TABLE II

Table to be used for the calculation of multiple interference within a uniform lattice of transmitters

Let D = side of equilateral triangle lattice i.e. the minimum spacing between transmitter sites.

Let x = distance from wanted transmitter site to interfering transmitter sites in ring.

Ring Number	x/D	Number of Transmitters in Ring	Cumulative Total of Interfering Transmitters
1	1·0	6	6
2	1·73	6	12
3	2·0	6	18
4	2·65	12	30
5	3·0	6	36
6	3·46	6	42
7	3·61	12	54
8	4·0	6	60
9	4·36	12	72
10	4·58	12	84
11	5·0	6	90
12	5·20	6	96
13	5·29	12	108
14	5·57	12	120
15	6·0	6	126
16	6·08	12	138
17	6·25	12	150
18	6·56	12	162
19	6·93	6	168
20	7·0	18	186
21	7·21	12	198
22	7·55	12	210
23	7·81	12	222
24	7·94	12	234
25	8·0	6	240
26	8·19	12	252
27	8·54	12	264
28	8·66	6	270
29	8·72	12	282
30	8·89	12	294
31	9·0	6	300
32	9·17	12	312
33	9·54	24	336
34	9·64	12	348
35	9·85	12	360
36	10·0	6	366

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